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February 1993

Advanced Photon Source

A series of lines radiating from a point on the left towards the right edge of the page, creating a fan-like effect. The lines are of varying lengths and are filled with a gradient of gray, from light to dark.

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Experimental Facilities Division  
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## Introduction

The Advanced Photon Source (APS) Wiggler A is a 2.4-m long device with an 8.5-cm period. It satisfies the requirement of achieving a peak field of 1.0 Tesla in the initial phase of operation. This will result in a critical energy of  $E_c=32.6$  keV, and the device will provide radiation in a regime harder than that from the APS bending magnet ( $E_c=19.5$  keV). With  $B_{peak}=1.0$  T and  $\lambda_u=8.5$  cm, the deflection parameter  $K$  is about 7.9. This puts the device well in the wiggler regime because the first harmonic radiation from such a device will be at 0.17 keV, far below the critical energy. The fan of radiation from a wiggler is about  $2K/\gamma=1.16$  mrad in the horizontal direction, and on the order of  $1/\gamma=0.073$  mrad in the vertical direction. As such, a  $K$  of 7.9 represents a good balance between providing a continuous and smooth spectrum without overly spreading the radiation fan in the horizontal direction. As for the source size, the excursion of the positron beam caused by the wiggler field is given by  $\pm(K/\gamma)(\lambda_u/2\pi) = \pm 7.8$   $\mu\text{m}$ , which is negligible compared to the positron beam size in the horizontal direction. Thus, the positron beam ( $\sigma_x=342$   $\mu\text{m}$ ,  $\sigma_y=91$   $\mu\text{m}$ ) completely defines the source size for Wiggler A.

Wiggler A has the additional capability of varying the magnetic gap. This gives considerable flexibility to the users in changing its critical energy to lower values. For operation at large gap values, the device can also provide undulator radiation below 4 keV from the first harmonic.

## Spectral Characteristics at 1.0 T Field

Table 1 lists the parameters for Wiggler A operating at a 1.0 T peak field. Fig. 1 shows the on-axis brilliance spectrum one can expect from Wiggler A at this mode ( $E_c=32.6$  keV). A peak brilliance of about  $3 \times 10^{16}$  ph/s/0.1% BW/mrad<sup>2</sup>/mm<sup>2</sup> is obtained at 27 keV, and the brilliance stays above the  $1 \times 10^{16}$  level throughout the 3-100 keV range. This creates a nearly flat spectrum in the energy region of interest to most users. The brilliance is more than one order of magnitude higher than that from the APS

bending magnet throughout the 1-100 keV range and, at 100 keV, it is actually two orders of magnitude higher.

In a uniform dipole field like that in a bending magnet, the critical energy of the emitted photons is related to the magnetic field  $B_0$  by

$$E_c[\text{keV}] = 0.665 E^2[\text{GeV}] B_0[\text{T}]. \quad (1)$$

For a wiggler, the magnetic field varies in a sinusoidal fashion, and thus the critical energy of the wiggler radiation depends on the horizontal observation angle  $\theta$  as follows

$$E_c(\theta) = E_c(0) \sqrt{1 - \left(\frac{\gamma\theta}{K}\right)^2}, \quad (2)$$

where  $E_c(0)$  is the on-axis critical energy (32.6 keV, in this case). Thus, as one moves off-axis horizontally, the critical energy decreases (see Fig. 2) and the spectrum becomes softer. Fig. 3 shows the spectral flux through horizontal apertures of various sizes with the vertical acceptance completely open. Note that the horizontal apertures reduce the flux from the low energy part of the spectrum more than that from the high energy part, because low energy photons are generated even at large values of  $\theta$ . At 0.1-mrad horizontal acceptance, the flux is comparable to that from the APS bending magnet which accepts 6-mrad horizontally.

In the vertical direction, the photon distribution is similar to that from a bending magnet. The vertical opening angle is a function of the photon energy  $E$  and the distribution can be approximated by a Gaussian function with standard deviation given by

$$\sigma_\psi = \left(\frac{1}{\gamma}\right) 0.565 \left(\frac{E_c(\theta)}{E}\right)^{0.425}, \quad (3)$$

where  $E_c(\theta)$  is given by Eq. 2. An interesting result is that for a certain energy  $E$  the vertical opening angle actually reduces as one wanders off-axis horizontally. This is demonstrated in Fig. 4 which simulates the angular distribution of photons at 100 keV from Wiggler A. Note the elliptical shape of the photon distribution. Fig. 5 shows the spectral flux through vertical apertures of various sizes while the horizontal acceptance is open. At 100 keV, the flux is essentially unaffected until the vertical aperture is below 0.1 mrad. Thus, if one is interested in the high energy region, an appropriate vertical aperture can substantially reduce the power loading without sacrificing the photon flux. On the other hand, any aperture will affect the low energy region, but a horizontal

aperture may be a better choice in terms of power reduction and eliminating the higher harmonics from a monochromator.

### Capability to Adjust the Magnetic Gap

In most cases, Wiggler A will be used at a fixed magnetic gap, for instance at 2.1 cm gap which produces a peak field of 1.0 T and a critical energy of 32.6 keV. However, Wiggler A offers the additional capability of varying the gap, which means adjusting the critical energy  $E_c(0)$  to tailor to the users' needs. Fig. 6 shows the dependence of the critical energy on the gap opening assuming a hybrid magnetic structure, and the relating parameters are listed in Table 2 for various gap openings. At the minimum gap (1.55 cm) of the initial phase operation, a peak field  $\approx 1.36$  T and a critical energy of about 44 keV may be produced. During the mature phase operation (1.15 cm gap), the peak field may reach 1.7 T, which pushes the critical energy to 55 keV. This produces abundant high energy x-rays if needed for experiments, but it also increases the power loading and shielding requirements which must be considered before operating in these high field regimes.

The other possibility is to open up the gap and use Wiggler A for the low energy regions. At 3.2-cm gap, the peak field is 0.6 T and the critical energy is 19.5 keV, identical to that of the APS bending magnet. Further opening to a 4.8-cm gap will result in a 0.3-T field and a 9.8-keV critical energy. The on-axis brilliance in these cases are shown in Fig. 7, which indicates a peak brilliance of about  $3 \times 10^{16}$  can be readily tuned from 27 keV to 8 keV. Fig. 8 shows the corresponding angle-integrated flux for these three cases. If one is interested in energies around 10 keV, the ratio of the photon flux at 20 keV to that at 10 keV is about 40% when the field is 0.3 T, while it is still about 80% when the field is 1.0 T. The reduction is even more for higher energies.

Table 3 lists the parameters for Wiggler A operating at a field of 0.3 T. An important transition takes place when the peak field is reduced from 1.0 to 0.3 T. The device has moved from the wiggler regime to an undulator-like regime, as the deflection parameter  $K$  decreases from 7.9 to 2.4. Therefore, an undulator calculation is shown together with a wiggler calculation in Fig. 8 for the 0.3 T case, primarily to show that some structures may exist in the spectrum when  $K$  is small. In this particular case, the first harmonic of the undulator radiation appears at 1.4 keV while presumably one is interested in the region near the critical energy of 9.8 keV. The actual spectrum from the device will be somewhere in between the undulator approximation and the wiggler approximation presented here, as field errors tend to preferentially reduce the higher

harmonic structures. On the other hand, if the acceptance is less than the entire beam (which is the case shown in Fig. 8), the undulator structure will become sharper.

There are several options to reduce the undulator structure if it is not already washed out by field errors. The first one is not to use a small limiting aperture, which may be possible because the power loading is substantially reduced for a low peak field. The other alternative is to close the gap more and use a slightly larger  $K$ . This mode of operation could be considered because the ratio of the first harmonic energy  $E_1$  to the critical energy  $E_c$  is a very strong function of  $K$

$$\frac{E_1}{E_c} = \frac{1.354}{K(1 + K^2/2)}, \quad (4)$$

while the critical energy only increases linearly with the field (or  $K$ ). For instance at a 0.6-T field,  $K=4.8$  and the first harmonic energy is 0.45 keV. Operating at slightly higher field also has the advantage of more spectral flux being available as shown in Fig. 8. Finally, one can taper the device to disrupt the radiation coherence and broaden the undulator structure. Fig. 9 shows the brilliance spectrum at 0.3-T field with 0- and 4-mm tapering. Undulator structures at or above 10 keV have been greatly reduced and, if a large acceptance is used, the remaining structures will further be broadened and thus should not pose a serious problem to the experiments.

If the gap is opened further, one can actually use the device as an undulator and start to utilize the first or high harmonics radiation. Fig. 10 shows the peak brilliance of the first and the third harmonics as the gap is tuned to achieve various values of  $K$ . The first harmonic can cover up to 4 keV while the brilliance of the third harmonic is still above the  $1 \times 10^{17}$  ph/s/0.1%BW/mrad<sup>2</sup>/mm<sup>2</sup> level even at 10 keV. This could prove to be quite useful, particularly for those users requiring a low energy, high brilliance source.

### Thermal Load

The 8.5-cm-period APS Wiggler A as devised will deliver a wiggler radiation beam with a critical energy of 32.6 keV. The gap opening to achieve this critical energy is 2.1 cm. The total beam power is about 7.4 kW, and the peak *power density* is about 74 kW/mrad<sup>2</sup>. The beam power profile is shown in Fig. 11. The normal incident *heat flux* on a component 30 m from the source is about 81 W/mm<sup>2</sup>. Thus, this device at a 2.1-cm gap will deliver about twice the total power compared to the APS Undulator A while the peak power density is just over one-half. Since the engineering design considerations of front-end and beamline components are mainly determined by the peak

heat flux, Wiggler A should not constitute any *special* thermal management challenge beyond what is already encountered for the case of APS Undulator A.

The specifications of Wiggler A are given in Table 1. Figure 12 displays the variation of the beam power with the magnetic gap. Also shown on the same figure is the beam power that passes through horizontal slits of various sizes. It can be seen that at a gap of 2.1 cm, a 600- $\mu$ rad horizontal slit will reduce the beam power by about 40% while, as seen from the corresponding figure for the spectral flux (Fig. 3), about 35% of the 32.6 keV photons are absorbed. Thus, unlike the undulator case, horizontal slits in the wiggler case reduce the beam power at the expense of useful photon flux. However, if one is interested in the brilliance instead, horizontal slits can certainly be used. The opening size of a 600- $\mu$ rad horizontal slit at 30 m from the source is 18 mm.

The peak *power density* of the APS Wiggler A beam as a function of the gap opening is shown in Figure 13. The corresponding normal incidence peak *heat flux* at 30 m from the source can also be read from the y-axis on the right hand side in Figure 13.

Fig. 14 shows the power profile of the beam when the peak field is 0.3 T. Note the profile in the horizontal direction is narrower compared to the 1.0-T case (Fig. 11). When the peak field is below 0.35 T, there is less than 1 kW of total power.

Finally, if the magnetic gap is reduced to the mature phase gap opening of 1.15 cm, the power of the wiggler is about 22 kW, which is about 6 times that of APS Undulator A, but the power density will actually be about 10% less. If necessary, Wiggler A can operate in this region to provide a high critical energy beam of up to 55 keV.



Table 1. Source parameters for APS Wiggler A operating at 1.0 T peak field. Ring energy is 7 GeV and positron current is 100 mA.

Device	Wiggler A
Undulator Period, $\lambda_u$ [cm]	8.5
Number of Periods, N	28
Device Length, L [m]	2.4
Magnetic Gap [cm]	2.1
Maximum Magnetic Field [T]	1.0
Deflection Parameter, K	7.9
First Harmonic Energy $E_1$ [keV]	0.17
Critical Energy, $E_c$ [keV]	32.6
Total Power [kW]	7.4
Peak Power Density [kW/mrad <sup>2</sup> ]	73
Peak Normal Heat Flux @ 30 m [W/mm <sup>2</sup> ]	81

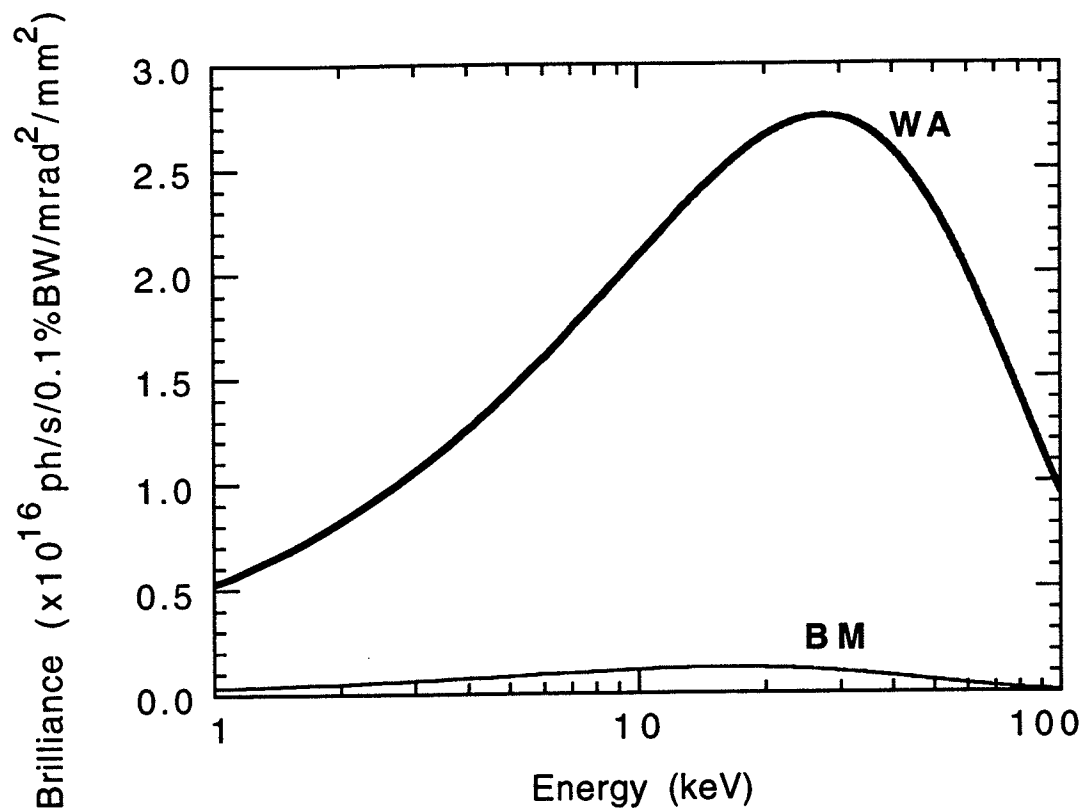
Table 2. Estimated values of peak field  $B_{\text{peak}}$ , deflection parameter  $K$ , critical energy  $E_c$ , first harmonic energy  $E_1$ , total power  $P_T$ , and peak power density  $dP/d\Omega$ , as a function of the gap opening (Wiggler A [ $\lambda_u=8.5$  cm], 7 GeV, 100 mA operation).

Gap [cm]	$B_{\text{peak}}$ [T]	$K$	$E_c$ [keV]	$E_1$ [keV]	$P_T$ [kW]	$dP/d\Omega$ [kW/mr <sup>2</sup> ]
1.15	1.69	13.4	55.1	0.065	21.3	123
1.20	1.64	13.1	53.6	0.069	20.1	120
1.30	1.56	12.4	50.8	0.077	18.1	113
1.40	1.48	11.7	48.1	0.085	16.2	107
1.50	1.40	11.1	45.6	0.095	14.6	102
1.55	1.36	10.8	44.4	0.100	13.8	99.2
1.60	1.33	10.5	43.2	0.105	13.1	96.6
1.70	1.26	9.99	41.0	0.117	11.8	91.6
1.80	1.19	9.48	38.9	0.129	10.6	87.0
1.90	1.13	9.00	36.9	0.143	9.57	82.6
2.00	1.08	8.55	35.1	0.158	8.63	78.4
2.10	1.02	8.12	33.3	0.174	7.80	74.5
2.50	0.838	6.65	27.3	0.256	5.23	61.0
3.00	0.659	5.23	21.5	0.402	3.23	47.9
3.50	0.524	4.16	17.1	0.610	2.04	38.0
4.00	0.421	3.34	13.7	0.891	1.32	30.5
4.80	0.303	2.41	9.88	1.49	0.684	21.8
5.00	0.280	2.23	9.14	1.67	0.586	20.1
6.00	0.195	1.55	6.36	2.60	0.283	13.8
7.00	0.142	1.12	4.61	3.46	0.149	9.86
8.00	0.107	0.85	3.49	4.11	0.086	7.27

Table 3. Source parameters for APS Wiggler A operating at 0.3 T peak field. Ring energy is 7 GeV and positron current is 100 mA. Quantities denoted by (\*) are evaluated at 1.4 keV.

Device	Wiggler A
Period, $\lambda_u$ [cm]	8.5
Number of Periods, N	28
Device Length, L [m]	2.4
Magnetic Gap [cm]	4.8
Magnetic Field [T]	0.3
Deflection Parameter, K	2.4
First Harmonic Energy $E_1$ [keV]	1.4
Critical Energy, $E_c$ [keV]	9.8
Total Photon Source Size, Standard Deviation [ $\mu\text{m}$ ]:*	
Horizontal, $\Sigma_x$	342
Vertical, $\Sigma_y$	91
Total Photon Source Divergence, Standard Deviation [ $\mu\text{r}$ ]:*	
Horizontal, $\Sigma_{x'}$	30.5
Vertical, $\Sigma_{y'}$	20.8
Total Power [kW]	0.66
Peak Power Density [kW/mrad <sup>2</sup> ]	22
Peak Normal Heat Flux @ 30 m [W/mm <sup>2</sup> ]	24

(a)



(b)

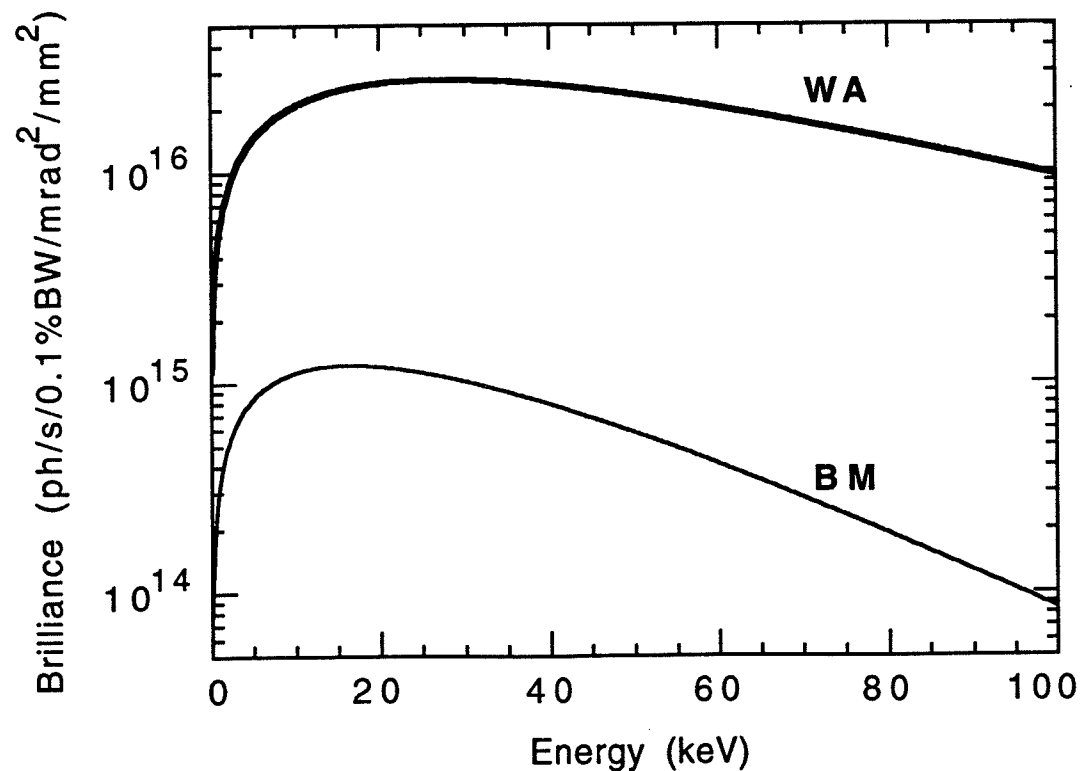
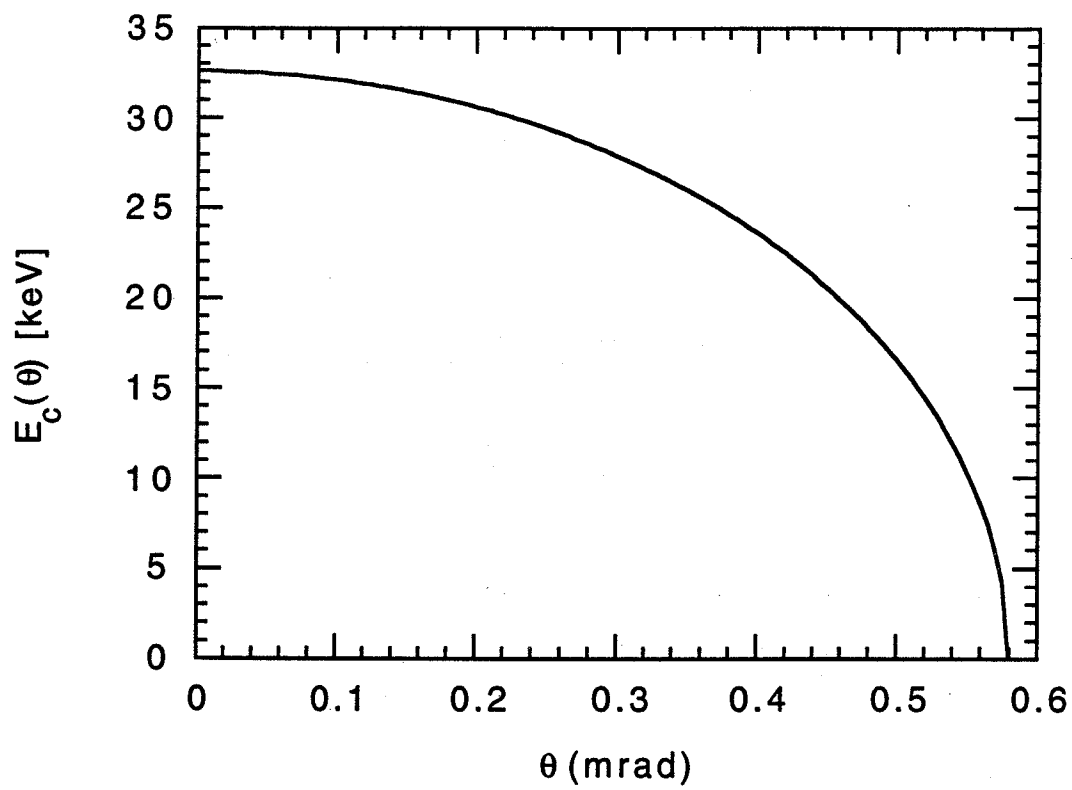


Fig. 1 Spectrum of the on-axis brilliance of Wiggler A at 1.0-T field compared to that of the APS bending magnet, on (a) linear-log and (b) log-linear scale (Wiggler A [ $\lambda_u=8.5$  cm], 7 GeV, 100 mA operation).



**Fig. 2** Dependence of the critical energy on the horizontal observation angle  $\theta$  for Wiggler A at 1.0 T field (Wiggler A [ $\lambda_u=8.5$  cm], 7 GeV operation).

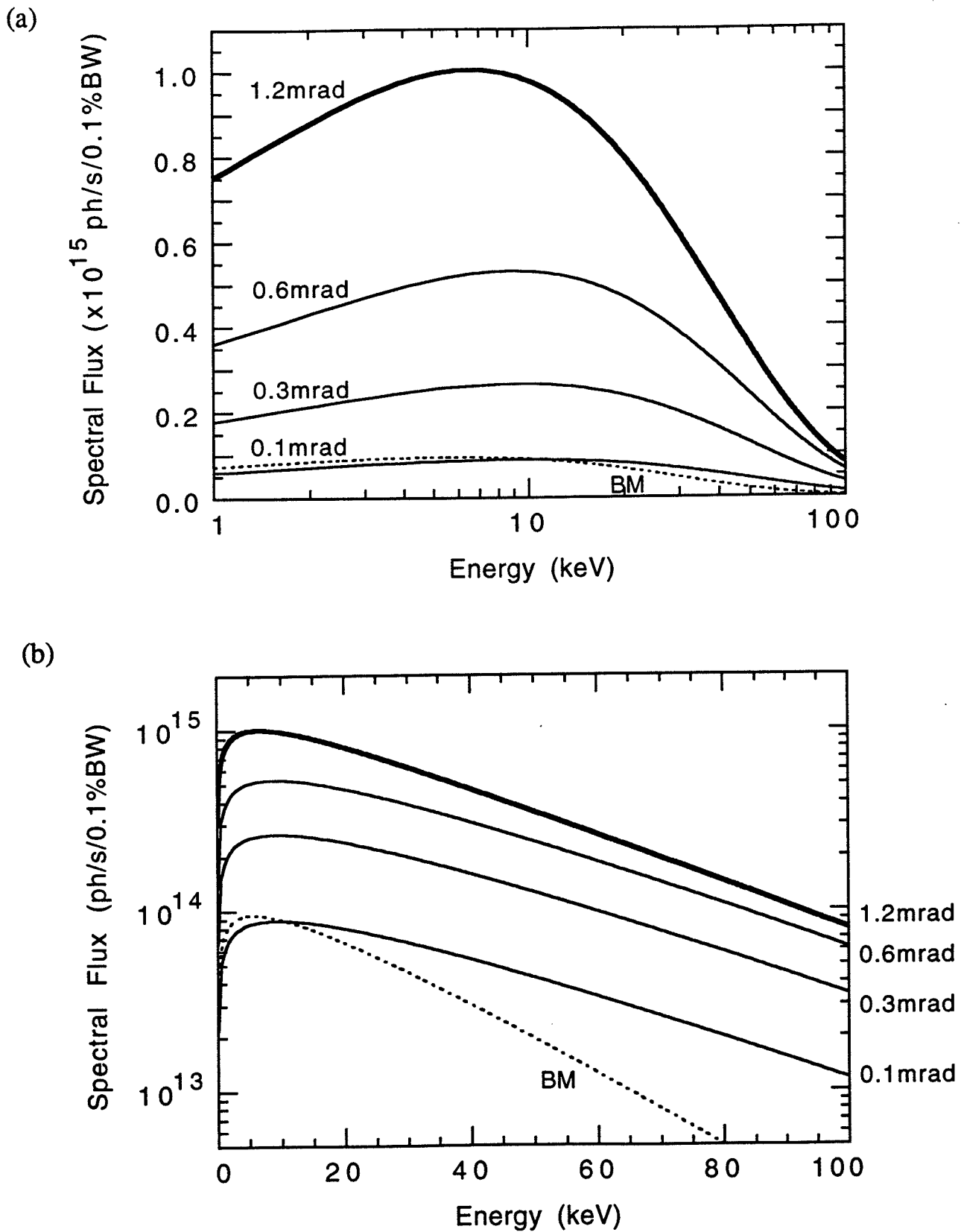


Fig. 3 Spectral flux of Wiggler A (1.0-T field) for various horizontal acceptances, on (a) linear-log and (b) log-linear scale. The vertical acceptance is completely open. These are compared to the APS bending magnet of 6 mrad horizontal acceptance (dashed line). (Wiggler A [ $\lambda_u=8.5$  cm], 7 GeV, 100 mA operation).

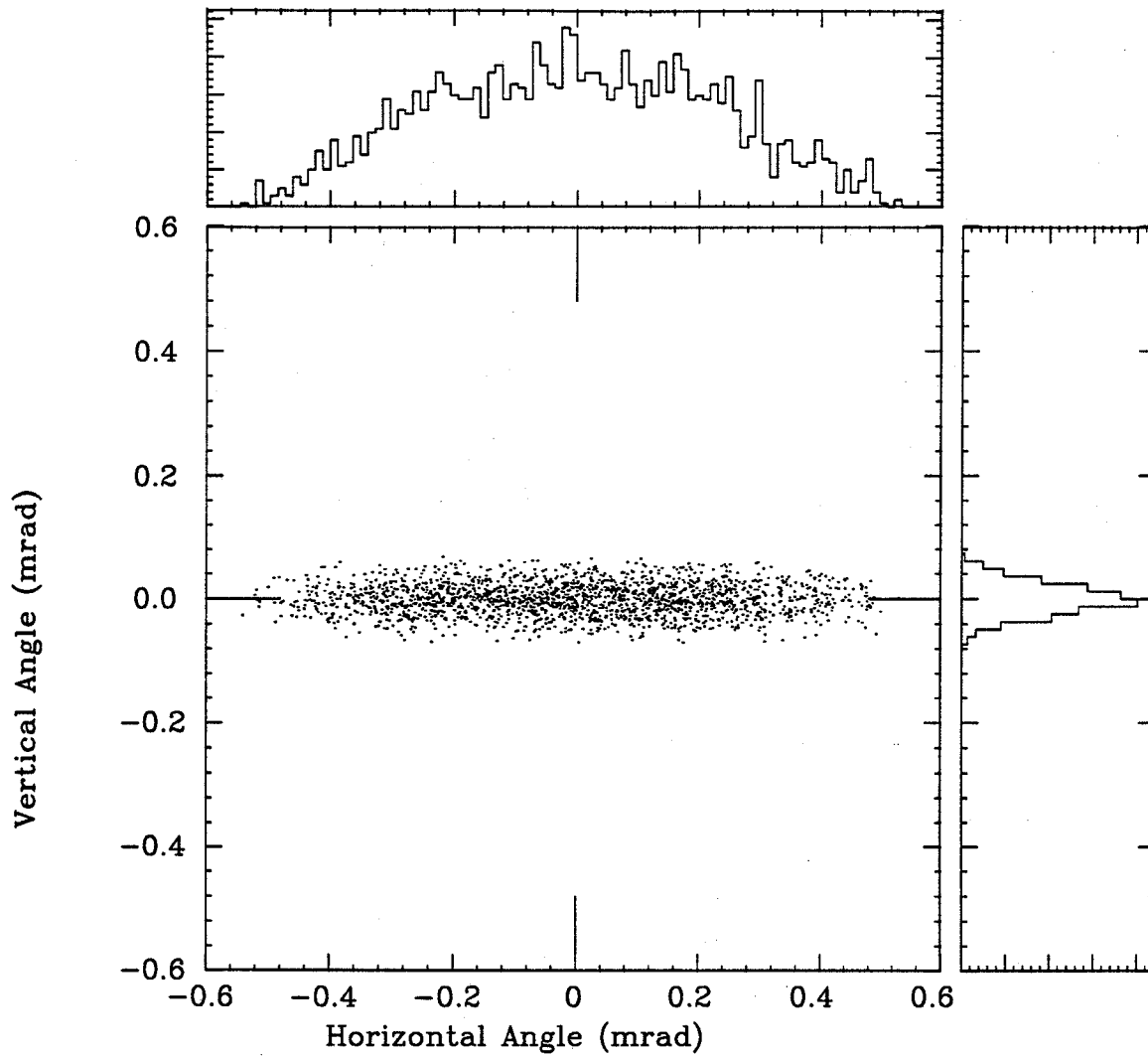


Fig. 4 Monte-Carlo simulation of the angular distribution of 100-keV photons generated by Wiggler A at 1.0 T field. The histograms are obtained by integrating along either the horizontal or the vertical direction (Wiggler A [ $\lambda_u=8.5$  cm], 7 GeV operation).

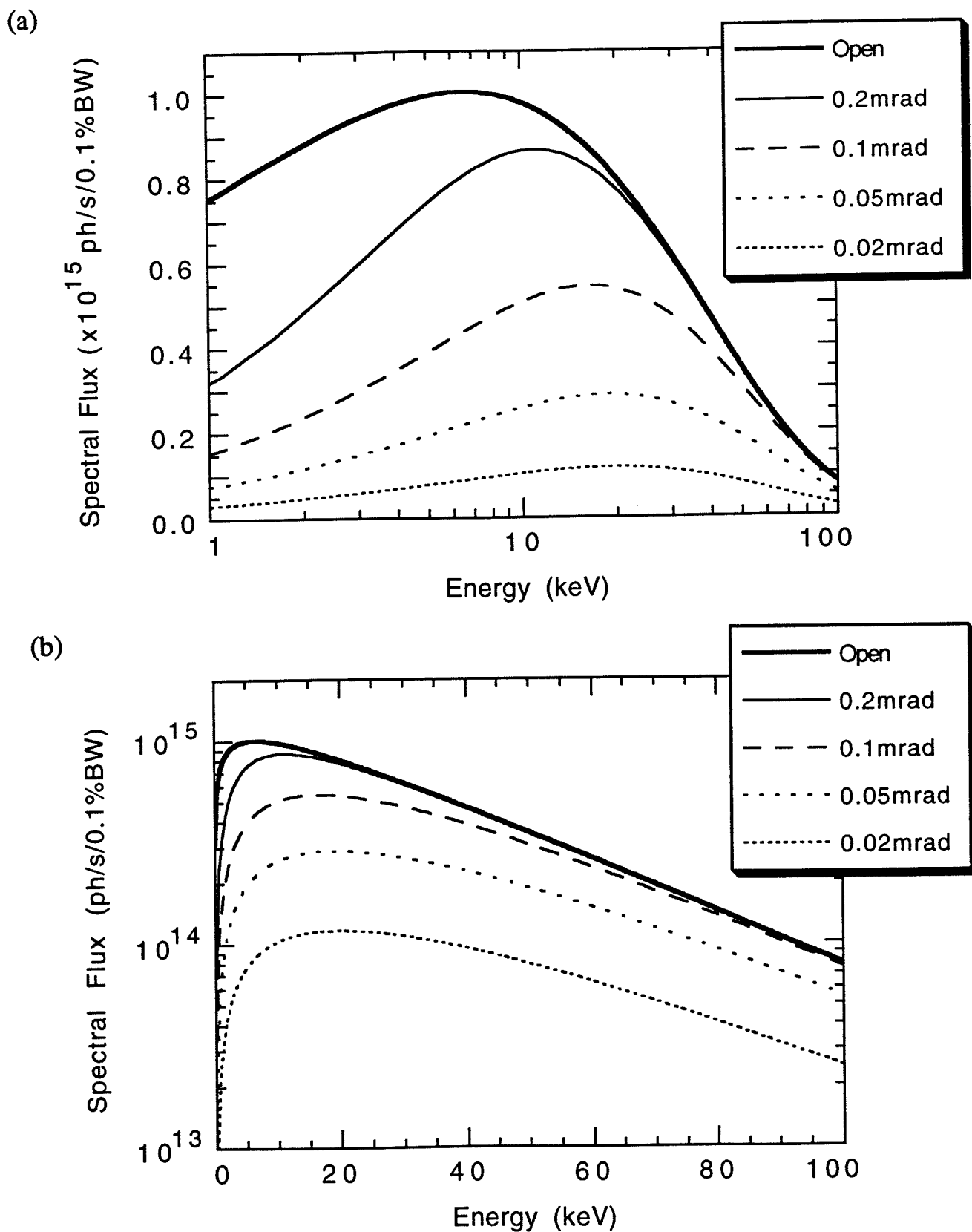


Fig. 5 Spectral flux of Wiggler A (1.0 T-field) for various vertical acceptances, on (a) linear-log and (b) log-linear scale. The horizontal acceptance is completely open (Wiggler A [ $\lambda_u=8.5$  cm], 7 GeV, 100 mA operation).



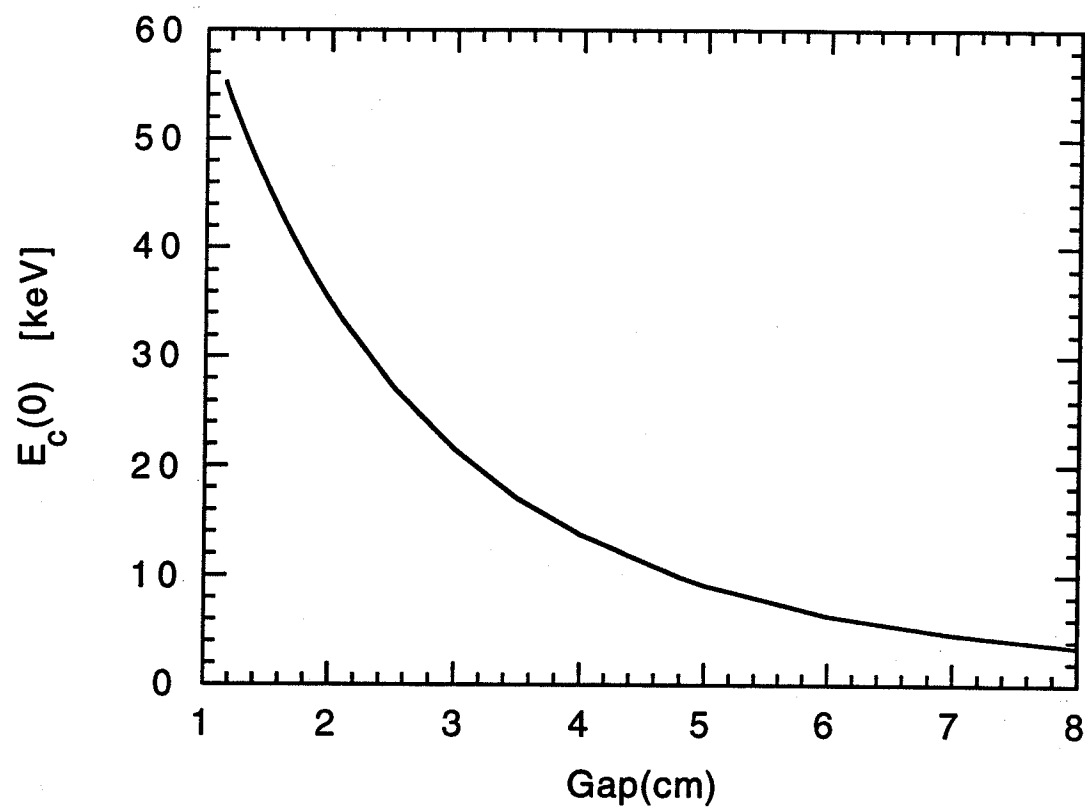
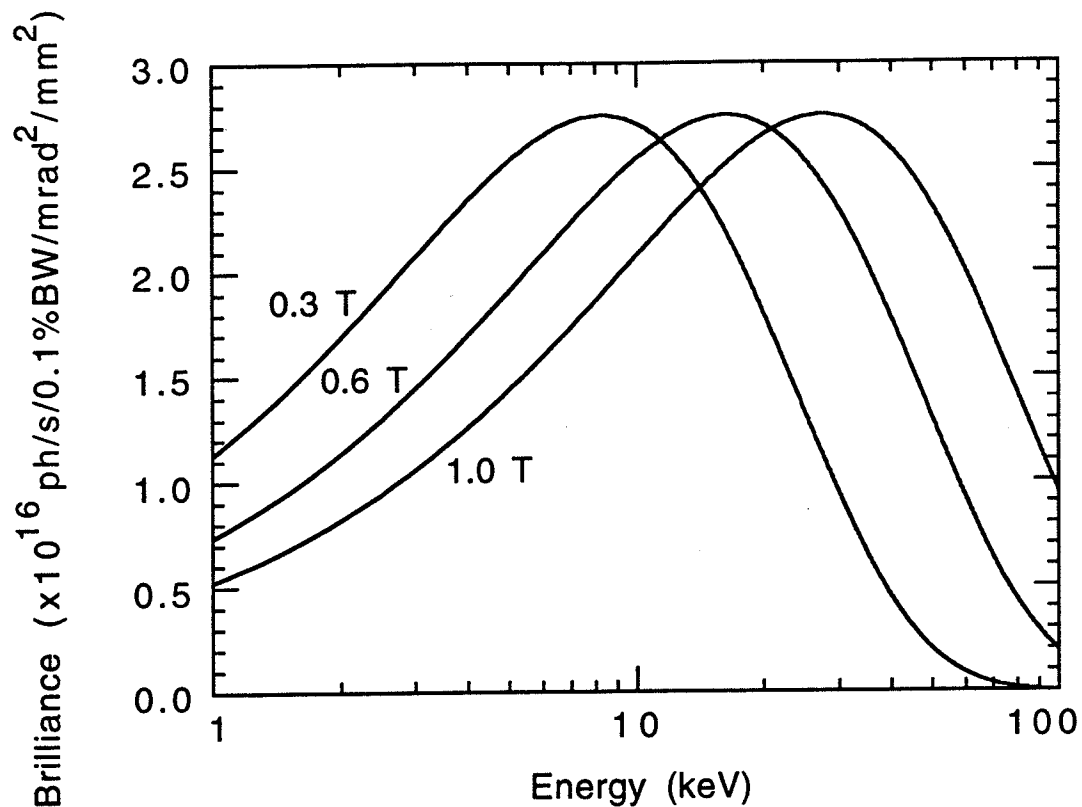


Fig. 6 Maximum critical energy  $E_c(0)$  as a function of the magnetic gap (Wiggler A [ $\lambda_u=8.5$  cm], 7 GeV operation).

(a)



(b)

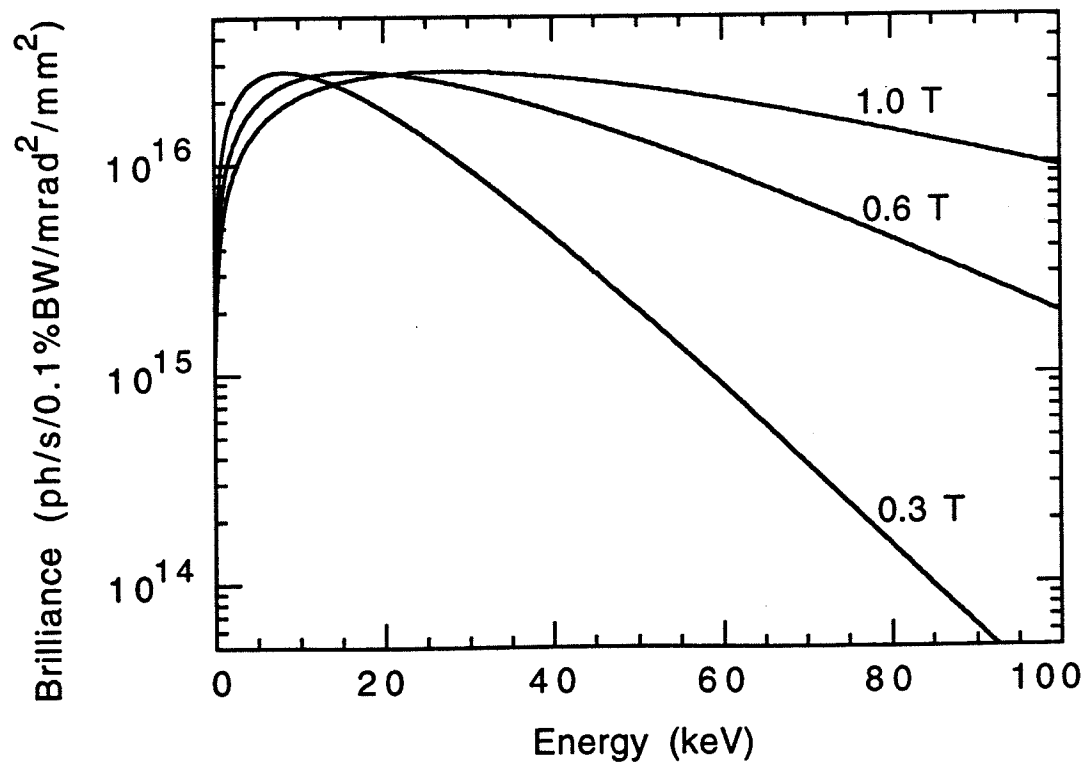
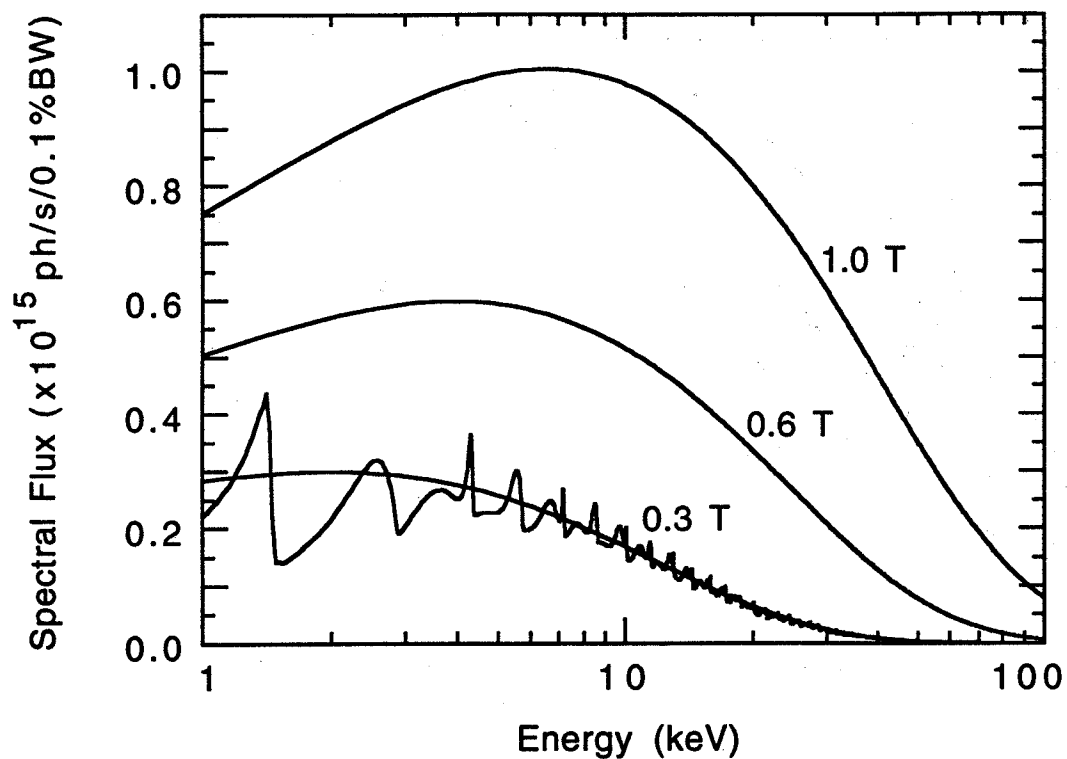


Fig. 7 On-axis brilliance spectra for Wiggler A operating at different peak fields, on (a) linear-log and (b) log-linear scale (Wiggler A [ $\lambda_u=8.5$  cm], 7 GeV, 100 mA operation).

(a)



(b)

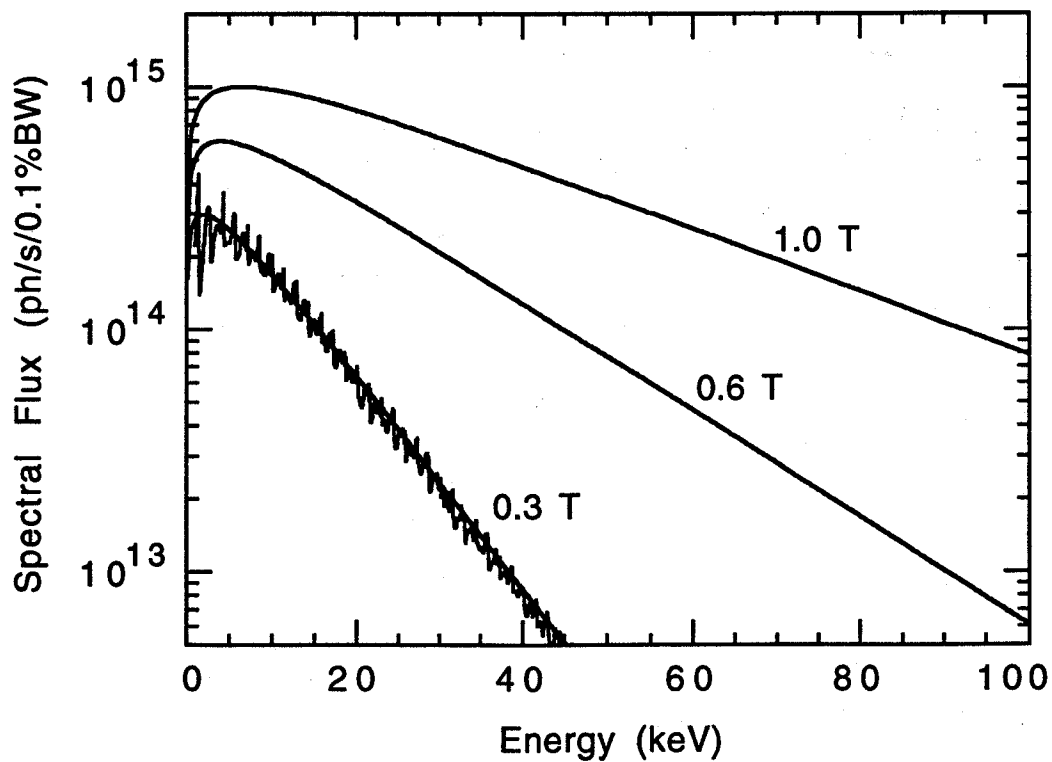


Fig. 8 Angle-integrated spectral flux for Wiggler A operating at different peak fields, on (a) linear-log and (b) log-linear scale. Undulator calculation assuming ideal field is also presented for the 0.3-T case (Wiggler A [ $\lambda_u=8.5$  cm], 7 GeV, 100 mA operation).

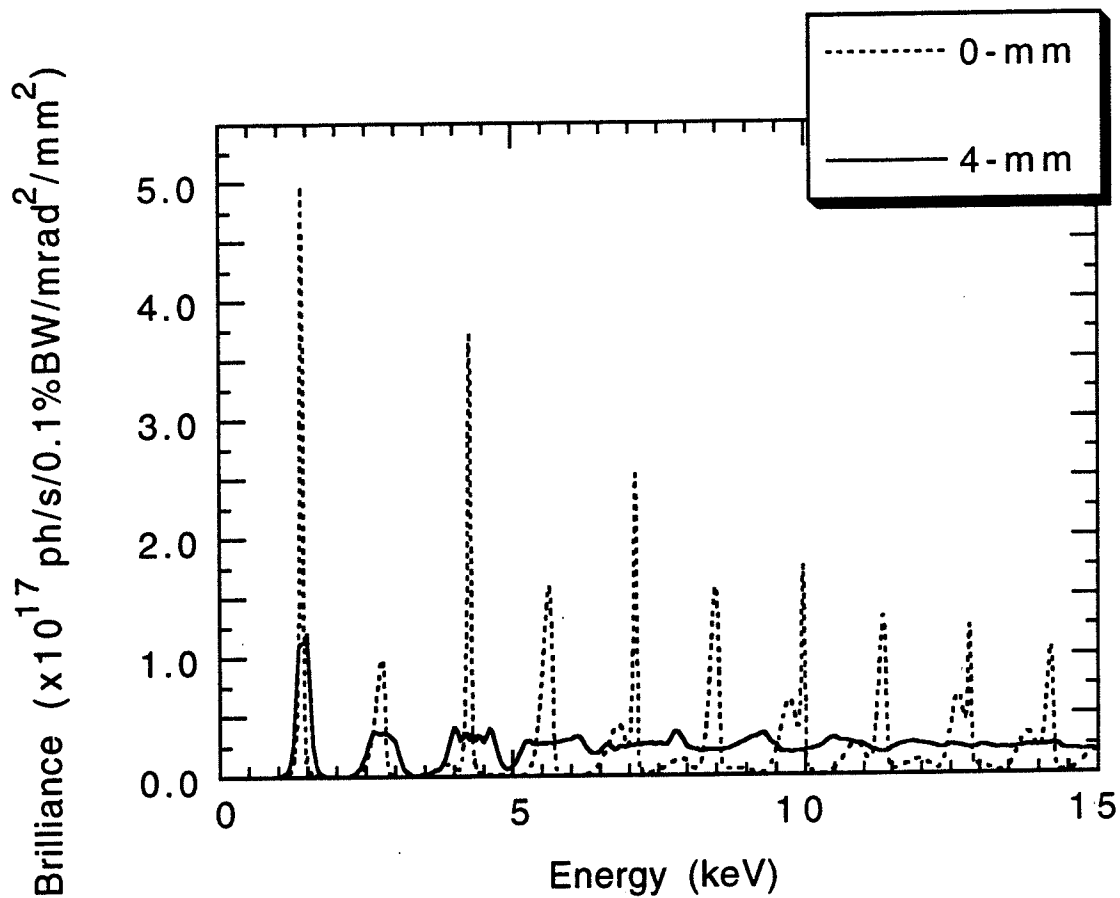


Fig. 9 On-axis brilliance of Wiggler A at an average field of 0.3 T for 0- and 4-mm gap tapering. The calculation assumed the APS beam emittance, but with no other field errors (Wiggler A [ $\lambda_u=8.5$  cm], 7 GeV, 100 mA operation).

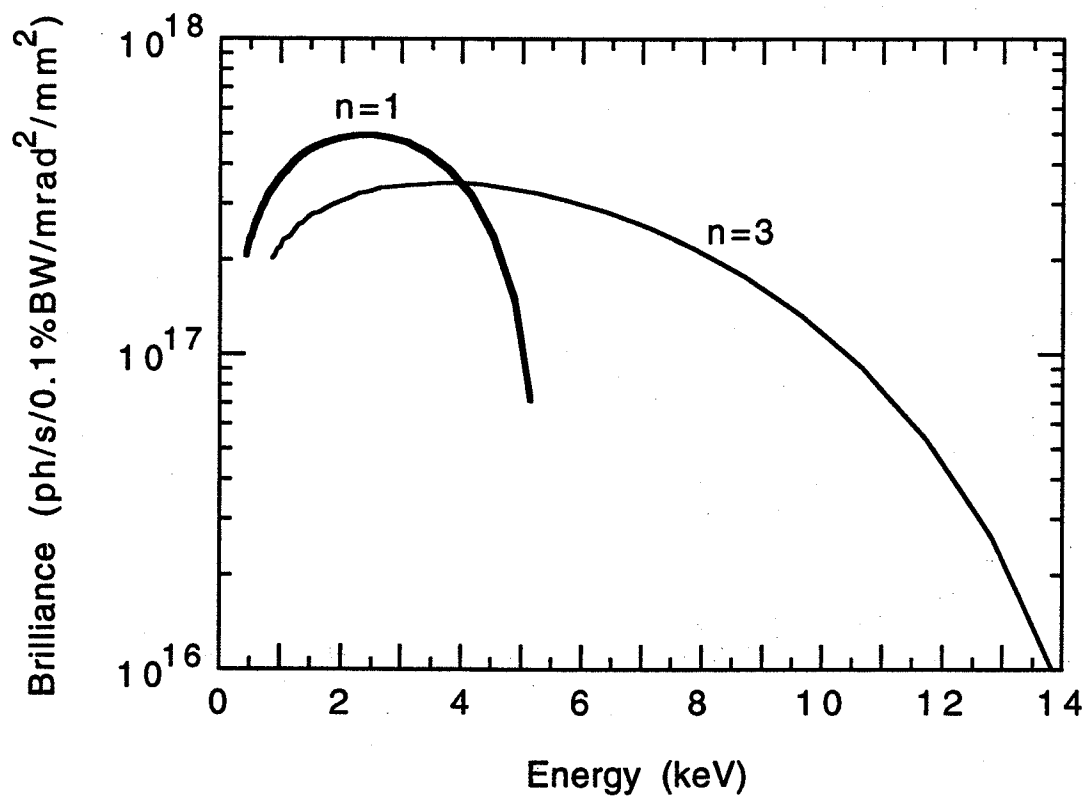


Fig. 10 Peak brilliance of the first and the third harmonic undulator radiation from Wiggler A operating in the small K regime. The gap must be changed to tune the energy of the harmonics (Wiggler A [ $\lambda_u=8.5$  cm], 7 GeV, 100 mA operation).

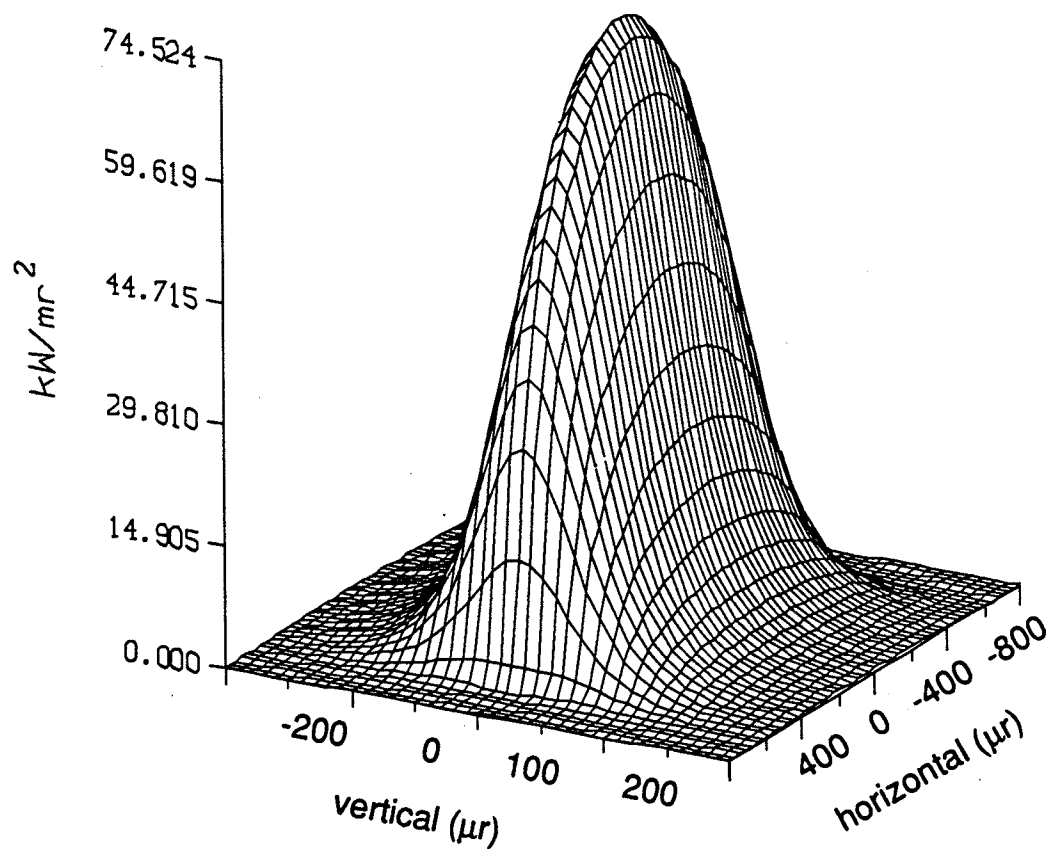


Fig. 11 Power profile of Wiggler A at 1.0 T field (Wiggler A [ $\lambda_u=8.5$  cm], 7 GeV, 100 mA operation).

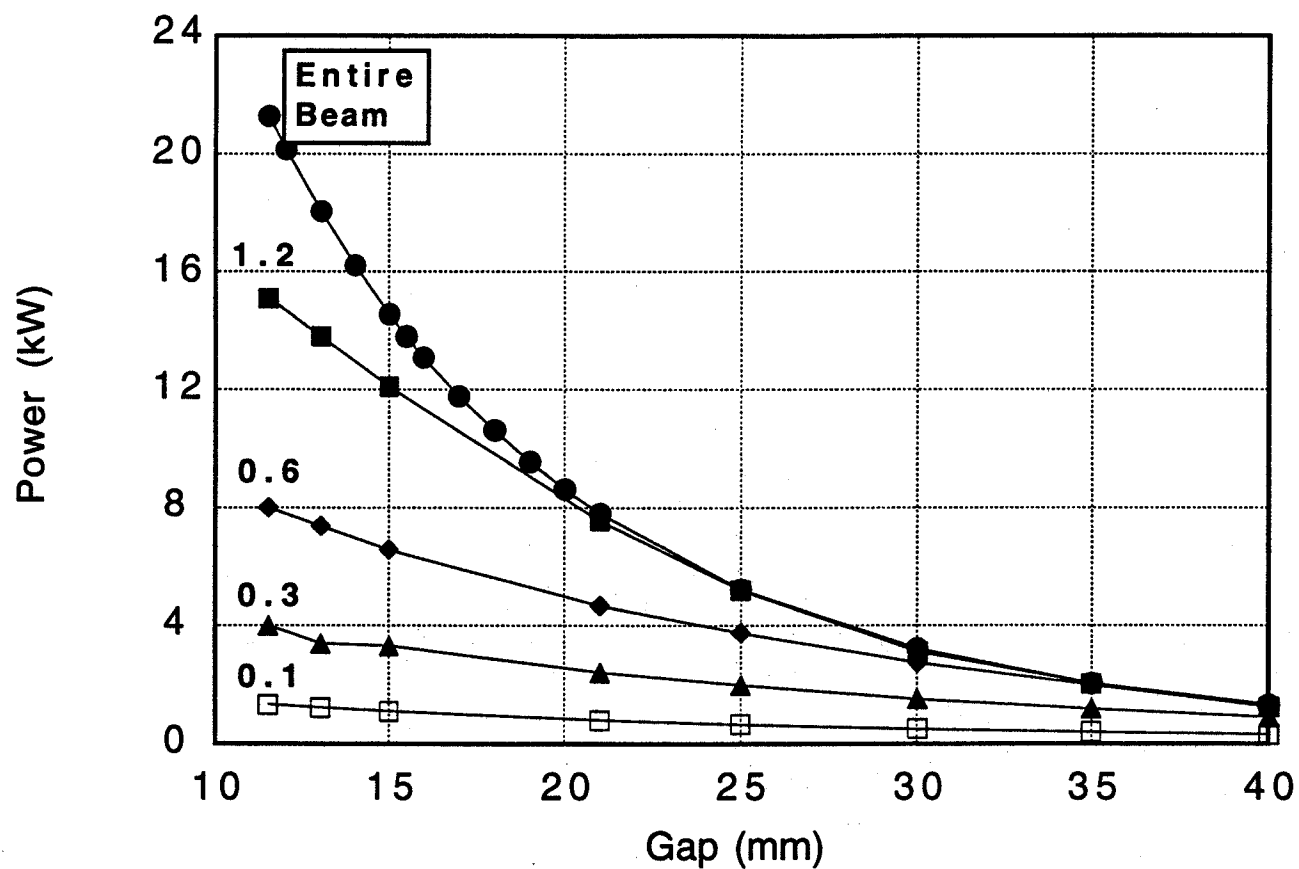


Fig. 12 Total power through horizontal apertures of various sizes, as a function of the gap opening. The acceptance of the apertures are given in mrad (Wiggler A [ $\lambda_u=8.5$  cm], 7 GeV, 100 mA operation).

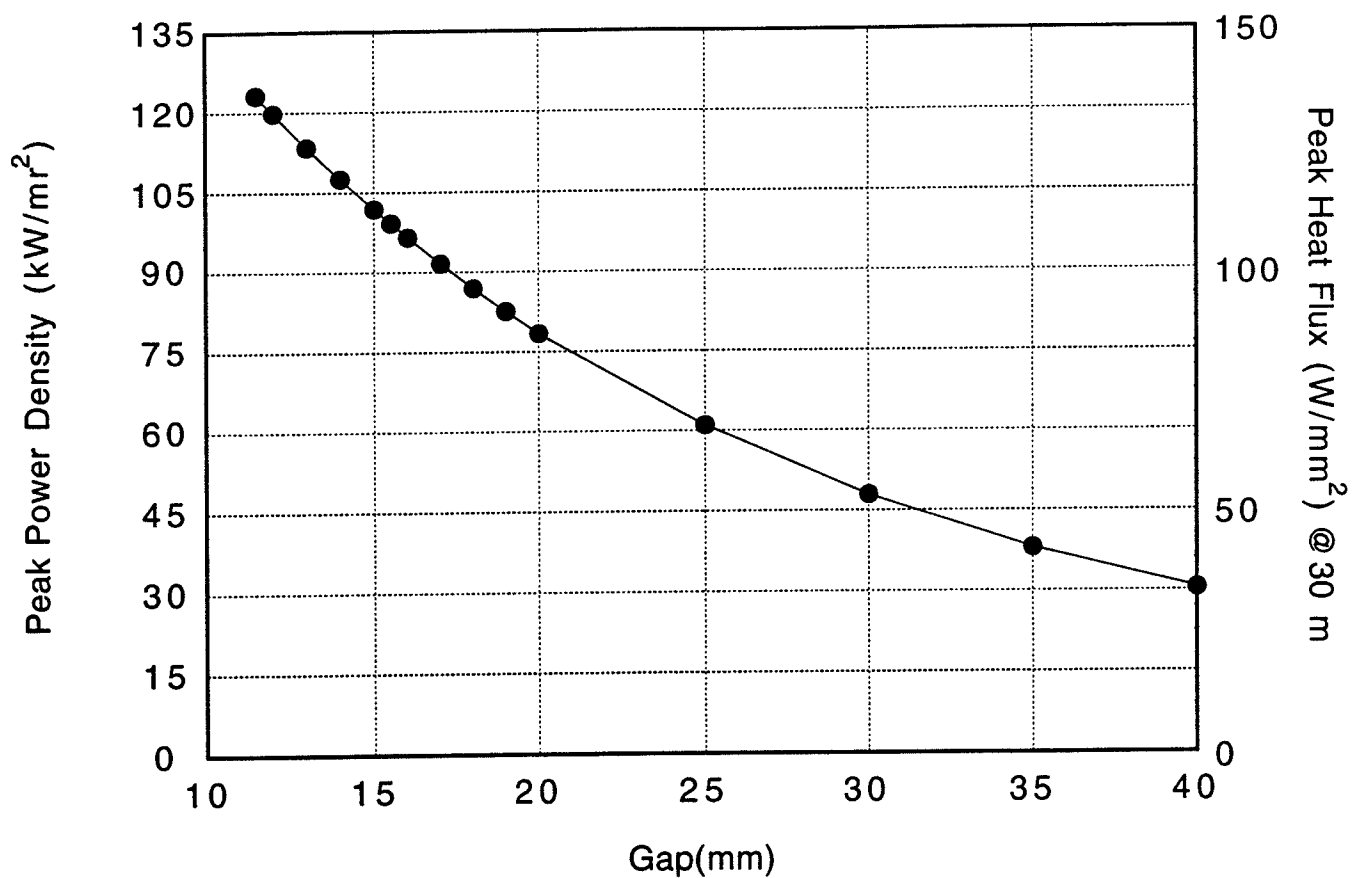


Fig. 13 Peak power density of Wiggler A as a function of the gap opening. The corresponding values for the peak heat flux normal to the beam at 30 m from the source can be read from the y-axis on the right (Wiggler A [ $\lambda_u=8.5$  cm], 7 GeV, 100 mA operation).



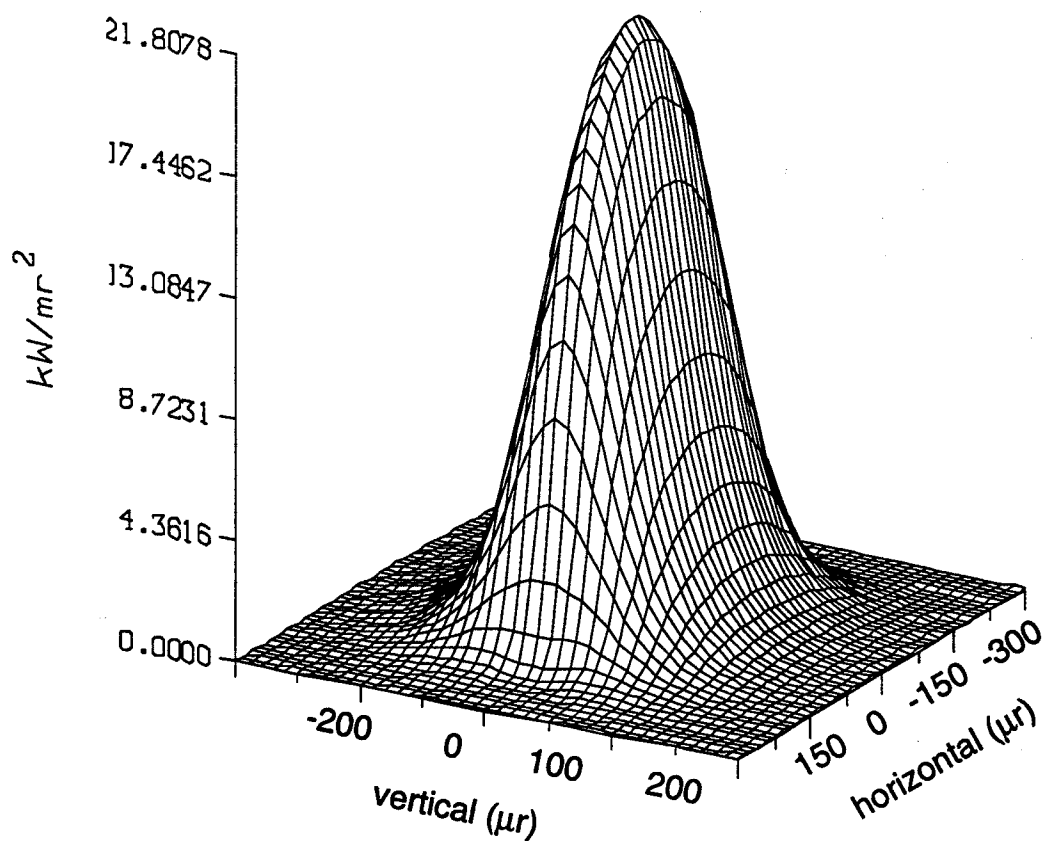


Fig. 14 Power profile of Wiggler A at 0.3 T field (Wiggler A [ $\lambda_u=8.5$  cm], 7 GeV, 100 mA operation).